

Fermilab

Fermi National Accelerator Laboratory (**Fermilab**), located just outside Batavia, Illinois, near Chicago, is a United States Department of Energy national laboratory specializing in high-energy particle physics. Since 2007, Fermilab has been operated by the Fermi Research Alliance, a joint venture of the University of Chicago, and the Universities Research Association (URA). Fermilab is a part of the Illinois Technology and Research Corridor.

Fermilab's Tevatron was a landmark particle accelerator; until the startup in 2008 of the Large Hadron Collider (LHC) near Geneva, Switzerland, it was the most powerful particle accelerator in the world, accelerating antiprotons to energies of 500 GeV, and producing proton-proton collisions with energies of up to 1.6 TeV, the first accelerator to reach one "tera-electron-volt" energy. At 3.9 miles (6.3 km), it was the world's fourth-largest particle accelerator in circumference. One of its most important achievements was the 1995 discovery of the top quark, announced by research teams using the Tevatron's CDF and DØ detectors. It was shut down in 2011.

In addition to high-energy collider physics, Fermilab hosts fixed-target and neutrino experiments, such as MicroBooNE (Micro Booster Neutrino Experiment), NOvA (NuMI Off-Axis ν_e Appearance) and SeaQuest. Completed neutrino experiments include MINOS (Main Injector Neutrino Oscillation Search), MINOS+, MiniBooNE and SciBooNE (SciBar Booster Neutrino Experiment). The MiniBooNE detector was a 40-foot (12 m) diameter sphere containing 800 tons of mineral oil lined with 1,520 phototube detectors. An estimated 1 million neutrino events were recorded each year. SciBooNE sat in the same neutrino beam as MiniBooNE but had fine-grained tracking capabilities. The NOvA experiment uses, and the MINOS experiment used, Fermilab's NuMI (Neutrinos at the Main Injector) beam, which is an intense beam of neutrinos that travels 455 miles (732 km) through the Earth to the Soudan Mine in Minnesota and the Ash River, Minnesota, site of the

Fermi National Accelerator Laboratory



A satellite view of Fermilab. The two circular structures are the Main Injector Ring (smaller) and Tevatron (larger).

Established	November 21, 1967 (as National Accelerator Laboratory)
Research type	Accelerator physics
Budget	\$546 million (2019) ^[1]
Field of research	Accelerator physics
Director	Nigel S. Lockyer
Address	P.O. Box 500
Location	Winfield Township, DuPage County, Illinois, United States 41°49′55″N 88°15′26″W﻿ / ﻿41.83194°N 88.25722°W﻿ / 41.83194; -88.25722
Nickname	Fermilab
Affiliations	U.S. Department of Energy

NOvA far detector. In 2017, the ICARUS neutrino experiment was moved from CERN to Fermilab, with plans to begin operation in 2020.^{[2][3]}

In the public realm, Fermilab is home to a native prairie ecosystem restoration project and hosts many cultural events: public science lectures and symposia, classical and contemporary music concerts, folk dancing and arts galleries. The site is open from dawn to dusk to visitors who present valid photo identification.

Asteroid 11998 Fermilab is named in honor of the laboratory.

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University of
Chicago
Universities
Research
Association

Nobel laureates

Leon Max Lederman

Website

www.fnal.gov (<http://www.fnal.gov/>)

Map



Location in Illinois

History

Weston, Illinois, was a community next to Batavia voted out of existence by its village board in 1966 to provide a site for Fermilab.^[4]

The laboratory was founded in 1969 as the **National Accelerator Laboratory**; it was renamed in honor of Enrico Fermi in 1974. The laboratory's first director was Robert Rathbun Wilson, under whom the laboratory opened ahead of time and under budget. Many of the sculptures on the site are of his creation. He is the namesake of the site's high-rise laboratory building, whose unique shape has become the symbol for Fermilab and which is the center of activity on the campus.



Robert Rathbun Wilson Hall

After Wilson stepped down in 1978 to protest the lack of funding for the lab, Leon M. Lederman took on the job. It was under his guidance that the original accelerator was replaced with the Tevatron, an accelerator capable of colliding protons and antiprotons at a combined energy of 1.96 TeV. Lederman stepped down in 1989 and remains Director Emeritus. The science education center at the site was named in his honor.

The later directors include:

- John Peoples, 1989 to 1996
- Michael S. Witherell, July 1999 to June 2005
- Piermaria Oddone, July 2005 to July 2013^[5]
- Nigel Lockyer, September 2013 to the present^[6]

Fermilab continues to participate in the work at the Large Hadron Collider (LHC); it serves as a Tier 1 site in the Worldwide LHC Computing Grid.^[7]

Accelerators

Current state

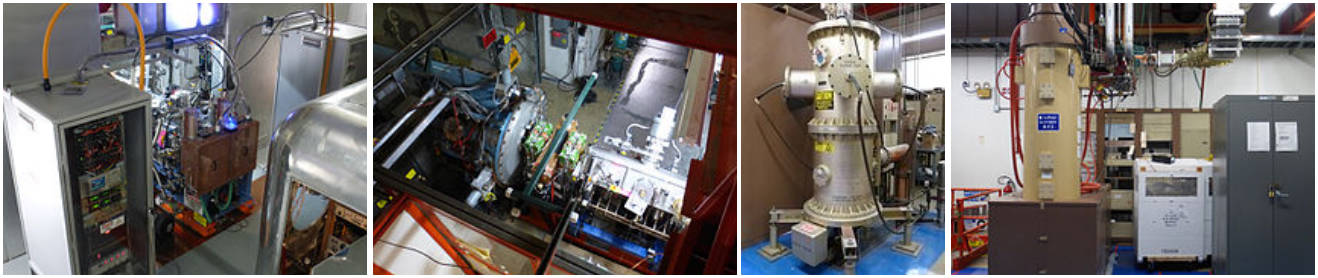
As of 2014, the first stage in the acceleration process (pre-accelerator injector) takes place in two ion sources which turn hydrogen gas into H^- ions. The gas is introduced into a container lined with molybdenum electrodes, each a matchbox-sized, oval-shaped cathode and a surrounding anode, separated by 1 mm and held in place by glass ceramic insulators. A magnetron generates a plasma to form the ions near the metal surface. The ions are accelerated by the source to 35 keV and matched by low energy beam transport (LEBT) into the radio-frequency quadrupole (RFQ) which applies a 750 keV electrostatic field giving the ions their second acceleration. At the exit of RFQ, the beam is matched by medium energy beam transport (MEBT) into the entrance of the linear accelerator (linac).^[8]

The next stage of acceleration is linear particle accelerator (linac). This stage consists of two segments. The first segment has 5 vacuum vessel for drift tubes, operating at 201 MHz. The second stage has 7 side-coupled cavities, operating at 805 MHz. At the end of linac, the

particles are accelerated to 400 MeV, or about 70% of the speed of light.^{[9][10]} Immediately before entering the next accelerator, the H^- ions pass through a carbon foil, becoming H^+ ions (protons).^[11]

The resulting protons then enter the booster ring, a 468 m (1,535 ft) circumference circular accelerator whose magnets bend beams of protons around a circular path. The protons travel around the Booster about 20,000 times in 33 milliseconds, adding energy with each revolution until they leave the Booster accelerated to 8 GeV.^[11]

The final acceleration is applied by the Main Injector [circumference 3,319.4 m (10,890 ft)], which is the smaller of the two rings in the last picture below (foreground). Completed in 1999, it has become Fermilab's "particle switchyard" in that it can route protons to any of the experiments installed along the beam lines after accelerating them to 120 GeV. Until 2011, the Main Injector provided protons to the antiproton ring [circumference 6,283.2 m (20,614 ft)] and the Tevatron for further acceleration but now provides the last push before the particles reach the beam line experiments.



Two ion sources at the Beam direction right to A 7835 A 12 MW klystron used
 center with two high- left: RFQ (silver), MEBT power at the second stage of
 voltage electronics (green), first drift tube amplifier that linac^[9]
 cabinets next to them^[12] linac (blue)^[12] is used at the
 first stage of
 linac^[9]



A cutaway view of the Booster ring^[14]
 805 MHz side-couple
 cavities^[13]

Fermilab's accelerator rings.
 The main injector is in the
 foreground, and the
antiproton ring and Tevatron
 (inactive since 2011) are in
 the background.

Proton improvement plan

Recognizing higher demands of proton beams to support new experiments, Fermilab began to improve their accelerators in 2011. Expected to continue for many years,^[15] the project has two phases: Proton Improvement Plan (PIP) and Proton Improvement Plan-II (PIP-II).^[16]

PIP (2011–2018)

The overall goals of PIP are to increase the repetition rate of the Booster beam from 7 Hz to 15 Hz and replace old hardware to increase reliability of the operation.^[16] Before the start of the PIP project, a replacement of the pre-accelerator injector was underway. The replacement of almost 40 year-old Cockcroft–Walton generators to RFQ started in 2009 and completed in 2012. At the Linac stage, the analog beam position monitor (BPM) modules were replaced with digital boards in 2013. A replacement of Linac vacuum pumps and related hardware is

expected to be completed in 2015. A study on the replacement of 201 MHz drift tubes is still ongoing. At the boosting stage, a major component of the PIP is to upgrade the Booster ring to 15 Hz operation. The Booster has 19 radio frequency stations. Originally, the Booster stations were operating without solid-state drive system which was acceptable for 7 Hz but not 15 Hz operation. A demonstration project in 2004 converted one of the stations to solid state drive before the PIP project. As part of the project, the remaining stations were converted to solid state in 2013. Another major part of the PIP project is to refurbish and replace 40 year-old Booster cavities. Many cavities have been refurbished and tested to operate at 15 Hz. The completion of cavity refurbishment is expected in 2015, after which the repetition rate can be gradually increased to 15 Hz operation. A longer term upgrade is to replace the Booster cavities with a new design. The research and development of the new cavities is underway, with replacement expected in 2018.^[15]

PIP-II

The goals of PIP-II include a plan to delivery 1.2 MW of proton beam power from the Main Injector to the Deep Underground Neutrino Experiment target at 120 GeV and the power near 1 MW at 60 GeV with a possibility to extend the power to 2 MW in the future. The plan should also support the current 8 GeV experiments including Mu2e, g-2, and other short-baseline neutrino experiments. These require an upgrade to the Linac to inject to the Booster with 800 MeV. The first option is to add 400 MeV "afterburner" superconducting Linac at the tail end of the existing 400 MeV. This requires moving the existing Linac up 50 metres (160 ft). However, there are many technical issues with this approach. The preferred option is to build a new 800 MeV superconducting Linac to inject to the Booster ring. The new Linac site will be located on top of a small portion of Tevatron near the Booster ring in order to take advantage of existing electrical and water, and cryogenic infrastructure. The PIP-II Linac will have low energy beam transport line (LEBT), radio frequency quadrupole (RFQ), and medium energy beam transport line (MEBT) operated at the room temperature at with a 162.5 MHz and energy increasing from 0.03 MeV. The first segment of Linac will be operated at 162.5 MHz and energy increased up to 11 MeV. The second segment of Linac will be operated at 325 MHz and energy increased up to 177 MeV. The last segment of linac will be operated at 650 MHz and will have the final energy level of 800 MeV.^[18]



Prototypes of SRF cavities to be used in the last segment of PIP-II Linac^[17]

Experiments

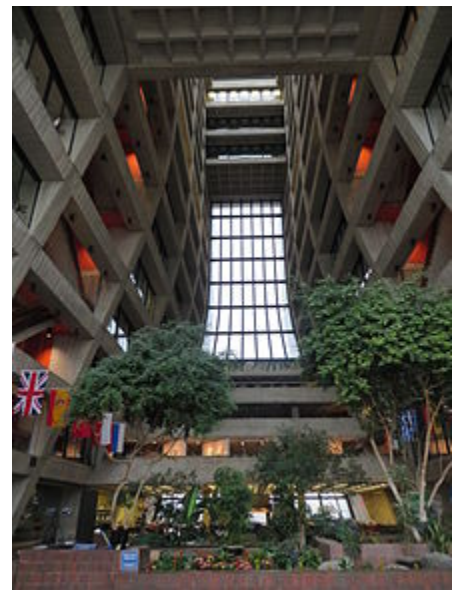
- Cryogenic Dark Matter Search (CDMS)^[19]
- COUPP: Chicagoland Observatory for Underground Particle Physics^[20]
- Dark Energy Survey (DES)^[21]
- Deep Underground Neutrino Experiment (DUNE), formerly known as Long Baseline Neutrino Experiment (LBNE)^[22]

- Holometer interferometer^[23]
- ICARUS experiment^[3] Originally located at the Laboratori Nazionali del Gran Sasso (LNGS), it will hold 760 tonnes of liquid Argon.
- MiniBooNE: Mini Booster Neutrino Experiment^[24]
- MicroBooNE: Micro Booster Neutrino Experiment^[25]
- MINOS: Main Injector Neutrino Oscillation Search^[26]
- MINERvA: Main INjector ExpeRiment with vs on As^[27]
- MIPP: Main Injector Particle Production
- Mu2e: Muon-to-Electron Conversion Experiment^[28]
- Muon g-2: Measurement of the anomalous magnetic dipole moment of the muon^[29]
- NOvA: NuMI Off-axis ν_e Appearance^[30]
- SELEX: SEgmented Large-X baryon spectrometer EXperiment, run to study charmed baryons
- Sciboone: SciBar Booster Neutrino Experiment^[31]
- SeaQuest^[32]
- ArgoNeuT: The Argon Neutrino Teststand detector^[33]

Architecture

Fermilab's first director, Robert Wilson, insisted that the site's aesthetic complexion not be marred by a collection of concrete block buildings. The design of the administrative building (Wilson Hall) was inspired by St. Pierre's Cathedral in Beauvais, France,^[34] though it was realized in a Brutalist style. Several of the buildings and sculptures within the Fermilab reservation represent various mathematical constructs as part of their structure.

The Archimedean Spiral is the defining shape of several pumping stations as well as the building housing the MINOS experiment. The reflecting pond at Wilson Hall also showcases a 32-foot-tall (9.8 m) hyperbolic obelisk, designed by Wilson. Some of the high-voltage transmission lines carrying power through the laboratory's land are built to echo the Greek letter π . One can also find structural examples of the DNA double-helix spiral and a nod to the geodesic sphere.



Interior of Wilson Hall

Wilson's sculptures on the site include *Tractricious*, a free-standing arrangement of steel tubes near the Industrial Complex constructed from parts and materials recycled from the Tevatron collider, and the soaring *Broken Symmetry*, which greets those entering the campus via the

Pine Street entrance.^[35] Crowning the Ramsey Auditorium is a representation of the Möbius strip with a diameter of more than 8 feet (2.4 m). Also scattered about the access roads and village are a massive hydraulic press and old magnetic containment channels, all painted blue.

Current developments

Fermilab is dismantling the CDF (Collider Detector at Fermilab) and DØ (Do experiment) facilities, and has been approved to continue moving forward with MINOS, NOvA, g-2, and Liquid Argon Test Facility.

LBNF/DUNE

Fermilab as of 2016 stands to become the world leader in Neutrino physics through the Deep Underground Neutrino Experiment at the Long Baseline Neutrino Facility. Other leaders are CERN, which leads in Accelerator physics with the Large Hadron Collider (LHC), and Japan, which has been approved to build and lead the International Linear Collider (ILC). Fermilab will be the site of LBNF's future beamline, and the Sanford Underground Research Facility (SURF), in Lead, SD, is the site selected to house the massive far detector. The term "baseline" refers to the distance between the neutrino source and the detector. The far detector current design is for four modules of instrumented liquid argon with a fiducial volume of 10 kilotons each. The first two modules are expected to be complete in 2024, with the beam operational in 2026. The final module is planned to be operational in 2027.^[36]

LBNF/DUNE program in neutrino physics plans to measure fundamental physical parameters with high precision and to explore physics beyond the Standard Model. The measurements DUNE will make is expected to greatly increase the physics community's understanding of neutrinos and their role in the universe, thereby better elucidating the nature of matter and anti-matter. It will send the world's highest-intensity neutrino beam to a near detector on the Fermilab site and the far detector 800 miles (1300 km) away at SURF.

Muon g-2

Muon g-2: (pronounced "gee minus two") is a particle physics experiment to measure the anomaly of the magnetic moment of a muon to a precision of 0.14 ppm, which will be a sensitive test of the Standard Model.

Fermilab is continuing an experiment conducted at Brookhaven National Laboratory to measure the anomalous magnetic dipole moment of the muon.

The magnetic dipole moment (g) of a charged lepton (electron, muon, or tau) is very nearly 2. The difference from 2 (the "anomalous" part) depends on the lepton, and can be computed quite exactly based on the current Standard Model of particle physics. Measurements of the electron are in excellent agreement with this computation. The Brookhaven experiment did

this measurement for muons, a much more technically difficult measurement due to their short lifetime, and detected a tantalizing, but not definitive, 3σ discrepancy between the measured value and the computed one.

The Brookhaven experiment ended in 2001, but 10 years later Fermilab acquired the equipment,^[37] and is working to make a more accurate measurement (smaller σ) which will either eliminate the discrepancy or, hopefully, confirm it as an experimentally observable example of physics beyond the Standard Model.

Central to the experiment is a 50 foot-diameter superconducting magnet with an exceptionally uniform magnetic field. This was transported, in one piece, from Brookhaven in Long Island, New York, to Fermilab in the summer of 2013. The move traversed 3,200 miles over 35 days, mostly on a barge down the East Coast and up the Mississippi.

The magnet was refurbished and powered on in September 2015,^[38] and has been confirmed to have the same 1300 ppm p-p basic magnetic field uniformity that it had before the move.^{[39]:4}

As of October 2015 the project is working on shimming the magnet to improve its magnetic field uniformity.^[39] This had been done at Brookhaven,^[40] but was disturbed by the move and must be re-done at Fermilab.

LHC Physics Centre (LPC)

The LHC Physics Center (LPC) at Fermilab is a regional center of the Compact Muon Solenoid Collaboration (the experiment is housed at CERN). The LPC offers a vibrant community of CMS scientists from the US and plays a major role in the CMS detector commissioning, and in the design and development of the detector upgrade.^[41]

Particle discovery

In the summer of 1977, a team of physicists, led by Leon M. Lederman, working on *Experiment 288*, in the proton center beam-line of the Fermilab fixed target areas, discovered the Upsilon (Bottom quark).^[42]



Muon g-2 building (white and orange) which hosts the magnet



Transportation of the 600 ton magnet to Fermilab

On 3 September 2008, the discovery of a new particle, the bottom Omega baryon (Ω_b^-) was announced at the DØ experiment of Fermilab. It is made up of two strange quarks and a bottom quark. This discovery helps to complete the "periodic table of the baryons" and offers insight into how quarks form matter.^[43]

Wildlife at Fermilab

In 1967, Wilson brought five American bison to the site, a bull and four cows, and an additional 21 were provided by the Illinois Department of Conservation. Some fearful locals believed at first that the bison were introduced in order to serve as an alarm if and when radiation at the laboratory reached dangerous levels, but they were assured by Fermilab that this claim had no merit. Today, the herd is a popular attraction that draws many visitors^[44] and the grounds are also a sanctuary for other local wildlife populations.^{[45][46]} A Christmas Bird Count has occurred at the lab every year since 1976.^[47]

Working with the Forest Preserve District of DuPage County, Fermilab has introduced barn owls to selected structures around the grounds.

In popular culture

Fermilab is first mentioned in season 12 episode 9 ("The Citation Negation") of *The Big Bang Theory* American television sitcom, where it was referred to by its previous name of National Accelerator Laboratory. It was first mentioned as "Fermilab" in season 12 episode 13 ("The Confirmation Polarization"). Fermilab is first mentioned in season 6 episode 16 ("The Tangible Affection Proof").

See also

- Big Science
- Center for the Advancement of Science in Space—operates the US National Laboratory on the ISS.
- CERN
- Fermi Linux LTS
- Scientific Linux
- Stanford Linear Accelerator Center

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External links

- [Fermi National Accelerator Laboratory](http://www.fnal.gov/) (<http://www.fnal.gov/>)
 - *Fermilab Today* Daily newsletter (<http://www.fnal.gov/pub/today/>)
 - Other Fermilab online publications (<http://www.fnal.gov/pub/publications/index.html>)

- [Fermilab Virtual Tour \(https://web.archive.org/web/20060316074800/http://www.fnal.gov/pub/about/tour/index.html\)](https://web.archive.org/web/20060316074800/http://www.fnal.gov/pub/about/tour/index.html)
 - [Architecture at the Fermilab campus \(http://www.fnal.gov/pub/about/campus/architecture.html\)](http://www.fnal.gov/pub/about/campus/architecture.html)
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